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A review on the relation between the energy and exergy efficiency analysis and the technical characteristic of the renewable energy systems

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ABSTRACT

One of the most important factors that can persuade human to use the renewable energy systems versus the conventional energy systems are the technical characteristics that include the reliability, maintenance requirements, availability, sustainability and environmental impacts. Technical characteristics of a system can affect the performance of the system. In the context of this work, the existent studies on the relation between the technical characteristic and the performance of the system are reviewed. It is concluded that there is a close relation between the performance of the system based on energy and exergy analysis and the technical characteristics. The systems which are more reliable and sustainable have less environmental impact and high energy and exergy efficiencies.

Contents

1. Introduction

The characteristics of any engineering system are defined by number of issues including; technical issues, economic issues, availability, reliability, sustainability, maintenance and environmental effects. These issues play an important role during the systems design and operation. Generally, improving system performance will have a direct effect on improving the system characteristics. Therefore, obtaining the optimum energy efficiency of the system has become one of the important issues for the sustainable development [1]. During the past decade, many researches have been conducted on the importance of increasing energy efficiency [2–5]. The results of the findings revealed that, the energy efficiency term by itself is not able to show a realistic picture of the system performance. Unlike energy, exergy is a measure of the quality of energy that can be considered to evaluate, analyze and optimize the system. Exergy analysis is utilized to define the maximum performance of a system and to specify its irriversibilities [6,7]. The exergy function itself is an 'extensive' property to measure the effectiveness or real value of an energy form [8].

Technically, exergy defines the maximum quantity of work than can be produced by a system when it comes to equilibrium with a reference environment [9,10]. Exergy analysis is known as a useful tool that can be utilized to evaluate the performance of any engineering system. The results can help to optimize

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Nomenclature

A	availability
D_P	deletion number
Ex	exergy
MTBF	mean time between failures
PEM	proton exchange membrane
PVS	photovoltaic system
R	reliability
SI	sustainability index
T	time
Λ	the failure rate

Subscript

D	destruction
In	input

the system efficiency by reducing inefficiencies [11–13]. During the past decade, exergy analysis was used for different applications to reduce system irreversibility such as; for industrial sector [5,14–16], residential sector [6], commercial sector [17], transportation sector [18].

The high energy costs of the conventional energy resources and their environmental impact has raised the interest of using alternative energy sources more than before. The potential future demand for these energy sources brings the necessity of evaluating the technical characteristics of each case, in details. In the context of this work, the studies on the relation between availability, reliability, sustainability, maintenance and environmental effects and the performance of the system are reviewed. It may be reported that to the best of authors' knowledge there is no work on the review of technical characteristics of the renewable energy power sources. Therefore, this review is expected to fill this gap.

2. General consideration of technical issues

Technical characteristics of the system can be arranged into reliability, maintenance requirements, availability, sustainability and environmental impacts. The maintenance and availability of the system both have significant effects on the reliability of it. It can also point out that since the environmental impacts of a system are less it can be considered as a sustainable one. The classification of the technical characteristics and their relations are illustrated in Fig. 1.

The probability of a system being inoperable due to an unscheduled event is called reliability. During the past decade, the importance of reliability aspects of conventional energy resources had a significant growth [19]. Generally, a mechanical system with a high degree of complexity reveals the importance of the reliability and its effect on the performance of the system. Reliability and maintenance are usually related to each other. Maintenance refers to the degree of required repairs that a system needs to meet the reliability specifications. The required level of maintenance is one of the important parameters during the system design. By increasing the system initial costs, the level of required maintenance decrease and the system will be more reliable. Availability $A(t|k)$, is also defined as the fraction of time a system is producing power compared to the fraction of time power is requested [20]. It is mostly determined by the availability of input source and generating capacity in desired time frame [21–23].

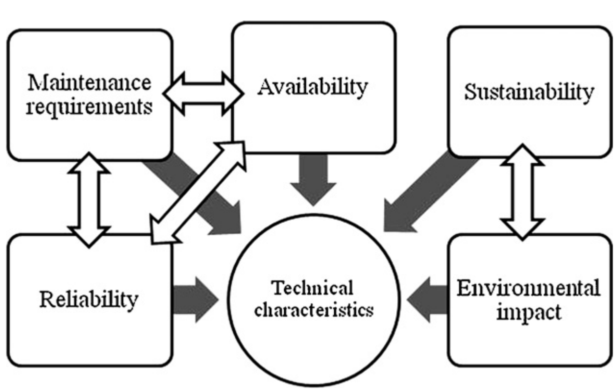

Fig. 1. The classification of the technical characteristics and their relations.

3. Reliability

As the renewable energy sources operate in highly stochastic, non-linear and multidisciplinary environments the reliability and performance assessment of them has become a significant issue [24]. Reliability ($R(t)$), is defined based on a binary approach, where a system can exist in two states of "up", when the system is completely operational at full performance and "down", when the system has failed. Hence, the probability of a system working in the "up" state is characterized by the reliability [25]. $R(t)$ refers to system survival before the first failure [24].

Ozgener and Ozgener [26] have performed a case study on a small wind turbine in turkey to evaluate its reliability utilizing the exergy analysis. The results from September 2002 to November 2003 show that the average technical availability of the system is around 94%, the real availability is around 52% and the capacity factor is around 12% while the exergy efficiency varied from 0 to 49%. The reliability analysis shows the failure rate of 2.28×10^{-4}/h and the reliability factor of 0.37 at 4380 h. Applying Eq. (1), the reliability of the system was calculated:

$$R(t) = \exp[-(\lambda_1 + \lambda_2 + \lambda_3 + \ldots + \lambda_n)t] = \exp\left(-\sum \lambda_i t\right) \qquad (1)$$

where λ is the failure rate that is equal to the mean time between failures (MTBF) and t is time (h). The reliability value $R(t)$ is equal to one when t is zero, and decrease continuously by increasing time and gets to the minimum of zero when t becomes very large [27]. Vittal and Teboul [24] have also analyzed the performance and reliability of wind turbines with the aim of Monte Carlo Methods based on System Transport Theory. Unlike the traditional approach, they simulate the performance and reliability of a wind turbine simultaneously. The results are useful in logistic planning for assessing the expected maintenance costs and evaluating the required spare parts. These results are found critical to developing effective maintenance and spare strategies.

Kaldellis et al. [28] have investigated the impact of acceptable reliability level on the stand-alone photovoltaic system (PVS) energy behavior and initial cost all around Greece. They found that a properly designed stand-alone PVS can solve the energy demand problem of many isolated customers. The results show that by increasing the initial cost of the PVS, the desired reliability will be increased as well. However, by decreasing the desired reliability value from 100% to 95%, the initial cost decreased significantly.

Tanrioven [19] has presented a systematic technique and a computer program for reliability and cost-benefits evaluation of renewable energy sources in an independent micro-grid system. In this work, he has conducted a reliability analysis and cost evaluation for the alternate energy sources. The results show that geographic locations and the operating constraints are the essential factors for determining the plant capacity. The findings can be used for type selection and hybrid configuration design of different energy resources.

Performance, failure and reliability of a wind farm with 15 wind turbine in India were analysed by Herbert et al. [29]. The reliability of the system is investigated based on the Weibull distribution technique and it is found that there is a direct relation between the reliability and the failure rate of the system. The real availability of the wind farm based on the performance analysis was reported to be 82.88% whilst the technical availability was calculated to be 94%. As the 79% of the failures are found related to mechanical components and 21% due to electrical components, it is concluded that reliable component and effective maintenance method can result in systems that are more efficient.

A study on availability and reliability aspects of seven wind farms in India was conducted by Mabel et al. [30]. The availability was defined as the percentage of time that is in power generating state. Eq. (2) was used to calculate the availability of the wind farm.

$$\text{Availability}\,(\%) = \left[\frac{\text{uptime}}{\text{uptime} + \text{downtime}}\right] \times 100 \tag{2}$$

The reliability of the system was computed based on daily energy generation and monthly energy generation data. It was pointed out that by improving the overall efficiency of the system the reliability will be enhanced. Therefore, the effects of increasing the hub heights on the overall efficiency and consequently on the reliability were analysed. It was resulted that an increment of 10 meter in hub heights will improve the efficiency by 12.04%. The reliability percentage was computed by using Eq. (3) and it was reported to be 53.29%.

$$\text{Reliability}\ (\%) = \left[\frac{\text{no. of hours} - \text{loss of load expectation}}{\text{no. of hours}}\right] \times 100 \tag{3}$$

4. Sustainability

Another important issue that must be considered during the system analysis is the sustainability of the system. Generally, a sustainable system can maintain a set of key characteristics within certain ranges indefinitely. The sustainability issue covers many different areas as it applies to a large number of human activities, including social, economic, scientific and engineering activities. A sustainable system may be referred to a reliable, environmentally friendly and cost-efficient system that employs the available energy resources effectively. During the past decade exergy analysis has been widely used to evaluate the sustainability of different systems and processes such as proton exchange membrane (PEM) fuel cells [31], thermal storage systems [32], drying systems [33], waste gas treatment systems [34] and industrial wastes [23]. Hepbasli [35] presents a comprehensive review on the exergetic analysis and evaluation of renewable energy sources for a sustainable future. The sustainability issue can also be studied in large scale overview. Zhang and Chen [36] have performed a physical sustainability assessment for the China society. Rosen and Dincer [37] have present the result of their investigation on co-relation between energy, exergy, environmental impact and sustainable development. They found that exergy analysis can provide a better picture to define the environmental impact.

A sustainability index (SI) is developed by Rosen et al. [9] as a parameter that shows the relation between sustainable development and exergy. SI can be computed by using Eq. (4):

$$\text{SI} = \frac{1}{D_\text{P}} \tag{4}$$

where D_P is the deletion number which was suggested by Connelly and Koshland [38] and characterized correlation between the exergy input and exergy. Using Eq. (5), the deletion number can be calculated:

$$D_\text{P} = \frac{Ex_\text{D}}{Ex_\text{in}} \tag{5}$$

In another study, Ojeda et al. [39] have analyzed the performance of sugarcane bagasse and its sustainability in the bioethanol production process via exergy analysis. They have used the same expression for exergy index as demonstrated by Rosen et al. [9]. The results of their survey show that the exergy analysis can be used to improve the sustainability index. The main goal of sustainable development is to reduce the harmful emissions associated with biofuels production processes.

The effects of the risk management, material conservation and control of the environmental impact on the reliability and sustainability of the system are illustrated in Fig. 2. It can be clearly seen that the mentioned parameters are lead to reliable and energy efficient system which has less environmental impacts that can be considered as the sustainable system. Reducing the failure rate of the system by enhancing the maintenance and deducting the risks will increase the reliability of the system.

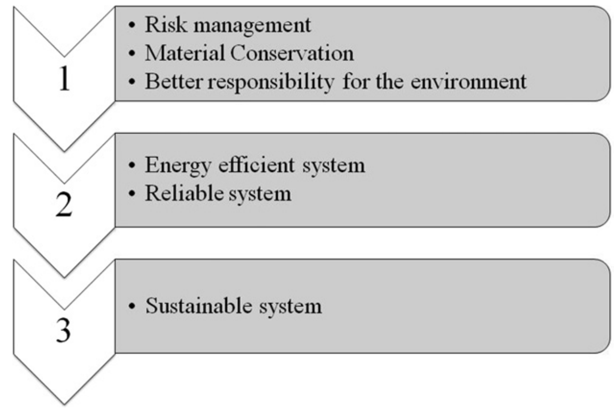

Fig. 2. The effective parameters on the reliability and sustainability of a system.

5. Environmental effects

The issues of energy production processes are not only limited to the global warming effect but also the environmental impact such as air pollutants, ozone depletion, and forest destruction are the important factors that must be taken into account during the system design [40]. To overcome these environmental problems utilizing renewable energy resources is found to be one of the most effective ways. Therefore, there is a close relation between the sustainable development and utilization of renewable energy resources [41,42]. Sustainable development can be achieved by sustainable supply of energy resources with a reasonable cost and low negative environmental effects. Attaining the sustainable development is possible by more efficient system that can reduce the energy consumption and consequently can reduce the emissions of the pollutants as CO_2, SO_2, NOx and CFCs in long term [33]. The United Nations indicates the importance of using alternative environmentally benign energy systems that can effectively increase atmosphere-protection strategies [43].

There are different approaches to classify and identify the impacts of energy use which mainly divide to classification by source, by pollutant and by scale. It can be pointed out to the global climate change, air pollution, carbon dioxide emissions and greenhouse gases as the main environmental and social concerns of the principal energy sources (Table 1).

Table 1
Classifying the impact of energy [44].

Different approach of classification		
Source	Pollutant	Scale
• Oil • Natural gas • Coal • Nuclear power • Biomass • Hydroelectricity • Wind power • Tidal power • Geothermal energy • Solar energy	• Lead emission to atmosphere • Oil added to oceans • Cadmium emissions • Sulphur emissions • Methane flow to atmosphere • Carbon dioxide flow to atmosphere	• House hold scale • Work place scale • Community scale • Regional scale • Global scale

Table 2
Summary of the investigated studies.

Author	Investigated system	Investigated technical characteristic	Ref.
Ozengar and Ozengar	Wind turbine	Reliability	[26]
Kaldellis et al.	Stand alone photovoltaic system	Reliability	[28]
Tanrioven	Micro grid system	Reliability and cost benefits	[19]
Ojeda et al.	Bioethanol production	Sustainability	[39]
Midilli and Dincer	Fuel cells	Sustainability	[31]
Herbert et al.	Wind farm	Reliability and failure rate	[29]
Mabel et al.	Wind farm	Availability and reliability	[30]

Recently, the necessity of realizing the relation between exergy, energy and environmental impact has enhanced significantly [45,46]. Exergy can be defined as a form of environmental free energy [47]. Fig. 3 demonstrates the schematic relation between exergy, sustainability and environmental impact [9]. It can be clearly seen that by increasing exergy efficiency the sustainability increased and the environmental impact decrease. A system with 100% exergy efficiency is completely reversible and has no environmental effect and therefore sustainability approaches to infinity. On the other hand, a system with zero exergy efficiency will have massive environmental impact.

The investigated systems and technical characteristics are summarized in Table 2. It can be seen that the wind turbine and the wind farms are the fields that most of the reliability analysis are dedicated to. The reliability analysis is highly desirable for the wind energy systems and it can be achieved by controlling the failure rate and enhancing the maintenance skills.

Almost all the renewable energy sources are potentially sustainable, among the renewable sources biomass and geothermal energy should be utilize in a way to be sustainable. In comparison between the conventional energy sources, the renewable sources are more sustainable and have less environmental impacts. Hence, reliability and availability analysis are the fields that most studies focused on to investigate the renewable energy sources.

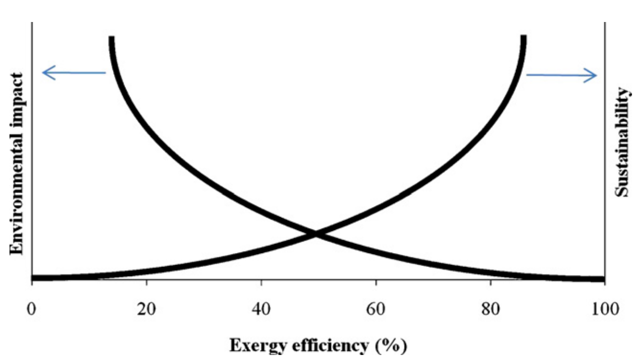

Fig. 3. Qualitative illustration of the relation between exergy efficiency, environmental impact and sustainability [9,48].

6. Future directions

There were a few works on the effects of the maintenance and availability of the systems on its performance. Evaluating the roles of maintenance on the energy and exergy efficiency of the system can determine the importance of the maintenance and ongoing costs of a system.

7. Concluding remarks

Based on the reviewed paper, it can be concluded that:

(1) The technical characteristics of a system can remarkably affect the performance of the system based on the energy and exergy analysis.
(2) Investigating the reliability and sustainability of the renewable energy systems can convince the importance of utilizing them versus their high initial cost.
(3) The sustainable systems, which have less environmental impact, have the higher energy and exergy efficiencies.
(4) The technical characteristics of the system affect the exergy efficiency of it more than the energy efficiency.

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